LHC Luminosity

and Energy Upgrade

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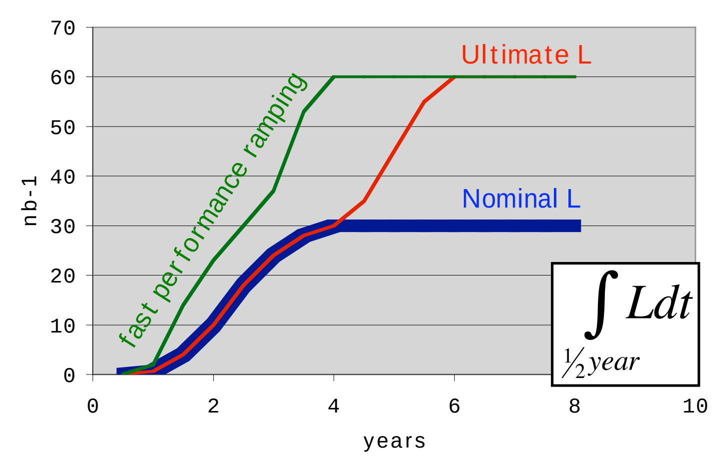
LHC performance and parameters

Parameter [units]	Nominal	Ultimate	Short bunch	Long bunch
No. of bunches n_b	2808	2808	5616	936
$p^+ \times$ bunch N_b [10^{11}]	1.15	1.7	1.7	6.0
Bunch spacing Δt_{sep} [ns]	25	25	12.5	75
Beam current [A]	0.58	0.86	1.72	1.0
E_{beam} [MJ]	366	541	1085	631
Beta at IP β^* [m]	0.55	0.50	0.25	0.25
Xing angle θ_c [μrad]	285	315	445	430
Bunch length [cm]	7.55	7.55	3.78	14.4
Piwinski ratio $\theta_c \sigma_s/(2\sigma^*)$	0.64	0.75	0.75	2.8
L lifetime τ_L [h]	15	10	6.5	4.5
L_{peak} [10^{34}cm^{-2}s^{-1}]	1.0	2.3	9.2	8.9
$T_{turnaround}$ [h]	10	10	5	5
Events per Xing	19.2	44.2	88	510
$\int_{\text{one year}} L\, dt$ [fb^{-1}]	66.2	131	560	410

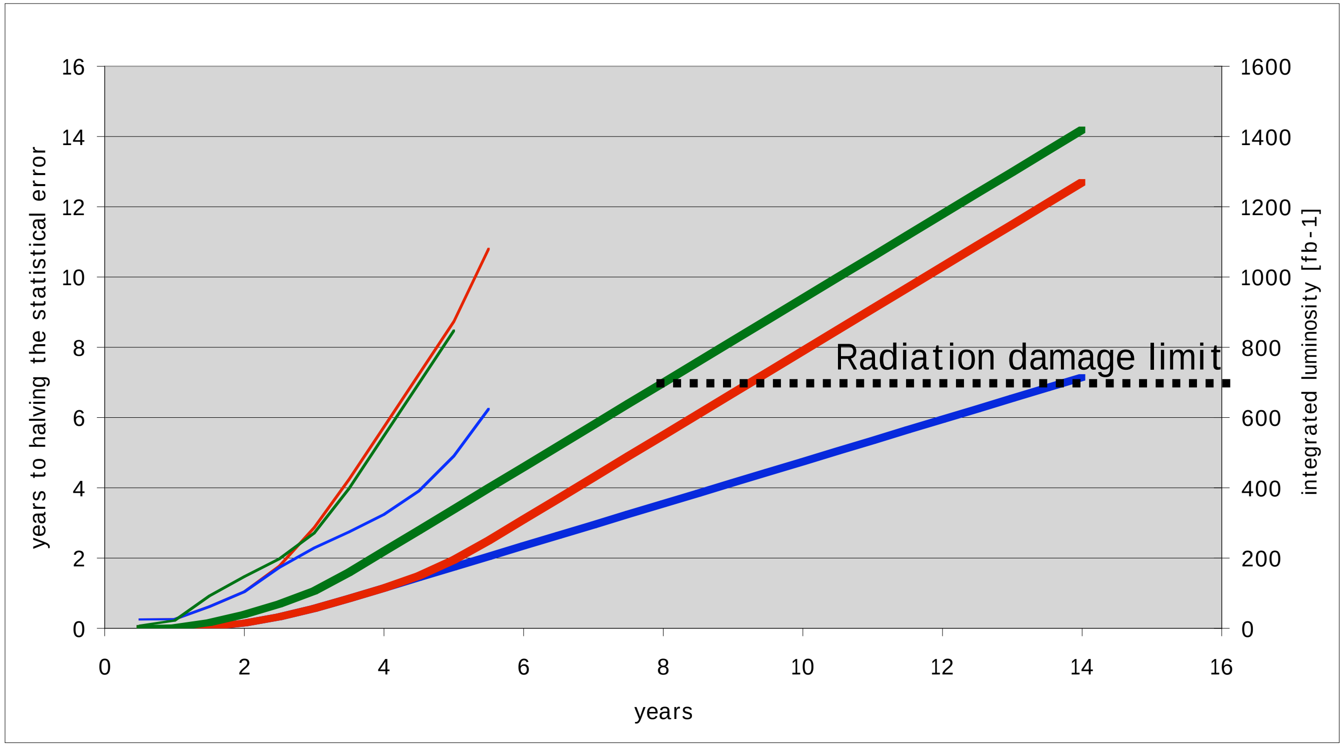
ε_n = 3.75 mm in all the options

LHC luminosity upgrade: why and when?



How fast performance is expected to increase:

- 4 y up to nominal *L*
- 4 y up to nominal *L* & 2 y up to ultimate *L*
- 4 y up to ultimate



- IR quadrupole lifetime ≥ 8 years owing to high radiation doses
- halving time of the statistical error ≥ 5 y already after 4-5 y of operation
- luminosity upgrade to be planned by the middle of next decade

Bunch scheme

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nominal and ultimate LHC

25 ns

baseline upgrade

back-up upgrade

more & shorter bunches

12.5 ns

plus: large luminosity gain with minimal event pile up & impact of θ_c

concern: e-cloud, cryogenic load, LRBB, impedance, collimation, machine protection

fewer & longer bunches

75 ns

plus: large luminosity gain with no e-cloud, lower I, easier collimation & machine protection

concern: larger event pile up, impedance

super-bunch

abandoned

plus: no e-cloud, lower I

concern: event pile up intolerable

Baseline for luminosity upgrade (short bunches)

$\sigma^* = \sqrt{\varepsilon \beta^*}$ beam size at the IP

$\varepsilon_n = \gamma\varepsilon = \gamma \frac{\sigma^2}{\beta}$ normalized emittance

$$L = \frac{\gamma n_b f N_b^2}{4\pi\beta^*} = \frac{\gamma}{4\pi\beta^*} \times \frac{N_b}{\varepsilon_n} \times I$$

Peak luminosity for head-on collisions

round beams, short Gaussian bunches

IR layout ($4\pi\beta^*$)

$\frac{N_b}{\varepsilon_n}$ beam brightness

- Head-on beam-beam
- Space-charge in injectors
- Transfer dilution

$I = n_b f N_b$ beam current

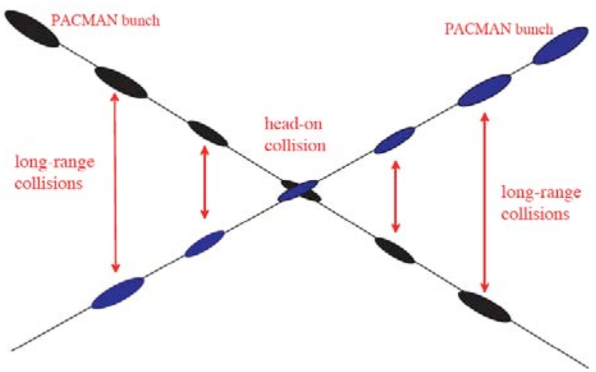
- Long range beam-beam
- Collective instabilities
- Synchrotron radiation
- Stored beam energy

Collisions with full crossing angle θ_c reduce the luminosity *L and* the beam-beam linear tune shift ΔQ_{bb} by the geometric factor *F*

$$L_{xing} = L_{head-on} \times F, \quad \Delta Q_{bb} = \xi_x + \xi_z \approx \frac{N_b r_p}{2\pi\varepsilon_n} \times F, \quad F \approx 1 \Big/ \sqrt{1 + \left(\frac{\theta_c \sigma_z}{2\sigma^*}\right)^2}$$

maximize *L* (below beam-beam limit) $\Longrightarrow$ short bunches & minimum θ_c

Minimal crossing angle



$$\xi_{head-on} = \frac{N_b r_p}{4\pi\gamma\varepsilon}, \quad \xi_{long-range} = \pm 2 n_{par} \frac{\xi_{head-on}}{(d/\sigma)^2}$$

relative beam-beam separation $\frac{d}{\sigma} \approx \theta_c \sqrt{\frac{\gamma\beta^*}{\varepsilon_n}}$

Beam-Beam Long-Range collisions:

- perturb motion at large betatron amplitudes
- cause 'diffusive' (or dynamic) aperture, high background, poor beam lifetime
- require larger crossing angles to preserve dynamic aperture
- require shorter bunches to avoid geometric luminosity loss

empiric formula of the diffusive aperture

$$\frac{d_{da}}{\sigma} \approx \frac{\theta_c}{\sigma_\theta} - 3\sqrt{\frac{n_{par}}{2\times 32} \times \frac{N_b}{10^{11}} \times \frac{3.75\mu m}{\varepsilon_n}}$$

$$\Rightarrow \frac{\theta_c}{\sigma_\theta} \approx 6 + 3\sqrt{\frac{I}{0.5A} \times \frac{3.75\mu m}{\varepsilon_n}}, \text{ with } \sigma_\theta = \sqrt{\frac{\varepsilon_n}{\gamma\beta^*}}$$

Backup for luminosity upgrade (long bunches)

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At the beam-beam limit the brilliance N_b/ε_n can be expressed in terms of ΔQ_{bb}

$$L \approx \frac{\gamma}{2r_p} \times \frac{\Delta Q_{bb} I}{\beta^*} \approx \frac{\pi\gamma f}{r_p^2} \frac{\Delta Q_{bb}^2 \varepsilon_n n_b}{\beta^*} \sqrt{1 + \left(\frac{\theta_c \sigma_s}{2\sigma^*}\right)^2}$$

maximize L (at the beam-beam limit) $\Rightarrow$ long bunches & large θ_c

Condition: I and N_b/ε_n not limited in the injectors neither in LHC (e.g. by e-cloud)

At high beam intensities or for large emittances, the performance will be limited by the angular triplet aperture A_{tripl}

$$L \approx \frac{\gamma}{2r_p} \Delta Q_{bb} I \times \min\left\{\frac{1}{\beta^*}, \frac{1}{\varepsilon}\left(\frac{A_{tripl}/\ell^*}{20 + \theta_c/\sigma_\theta}\right)\right\}$$

Interaction Region upgrade

The main goal is to reduce β^* by at least a factor 2

Options for magnet technology:

- NbTi 'cheap' upgrade, NbTi(Ta) (assessed technology, modest improvement)
- Nb_3Sn new IR magnets (new technology, consistent improvement)

factors driving IR design:

- minimize β^*
- minimize effect of LR collisions
- sustain large radiation power directed towards the IR magnets
- accommodate crab cavities and/or beam-beam compensators.
- local Q' compensation scheme?
- compatibility with upgrade path

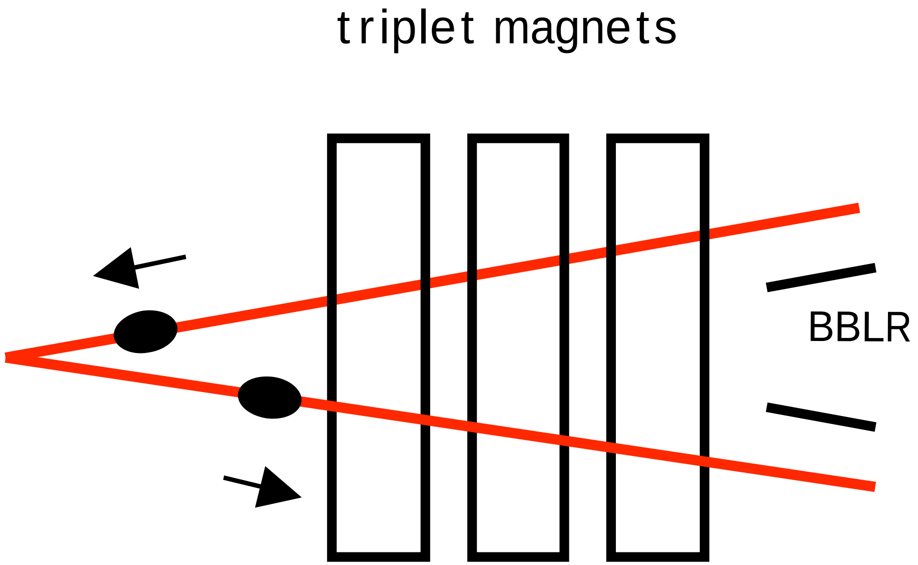
maximize magnet aperture, minimize distance l^* to IP

WEPCH104 and 138

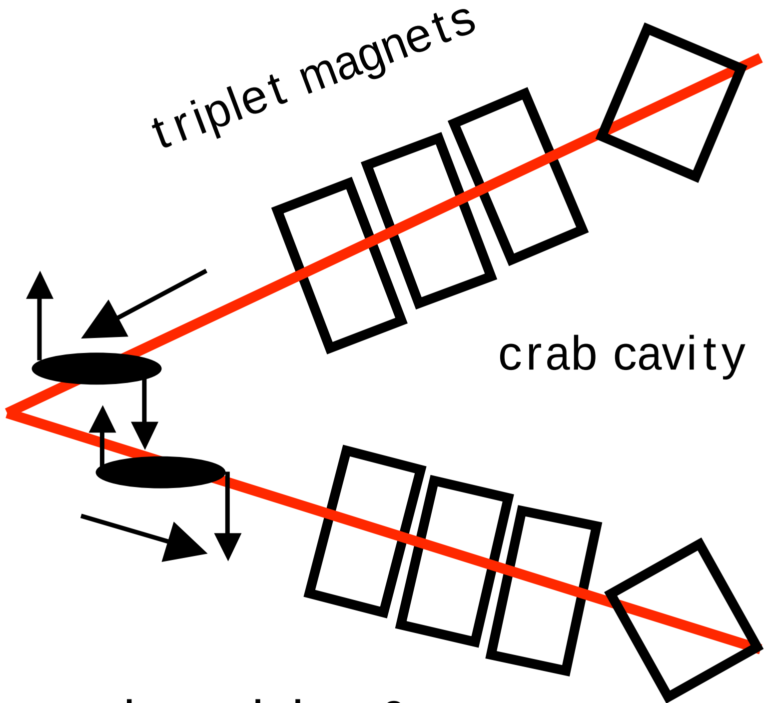
variants:

- quadrupole first
- dipole first
- flat beams with doublets or triplets (luminosity gain up to 30 %)
- D0 scheme (a dipole very close to IP) to reduce θ_c and increase F ← WEPCH094
- Slim quadrupoles (low gradient quadrupoles close to IP) to reduce β_{peak} ← WEPCH044
- reduced l^* to minimize β_{peak} ← WEPCH044

IR ‘baseline’ schemes

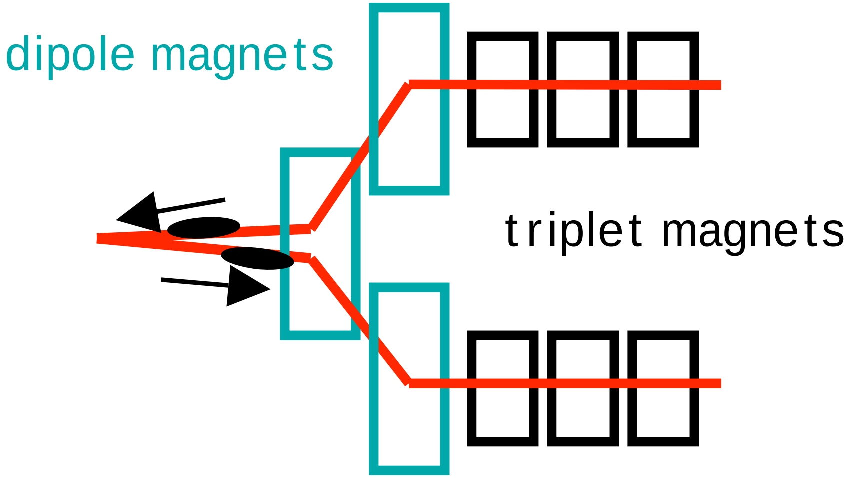


short bunches &
minimum crossing angle & BBLR



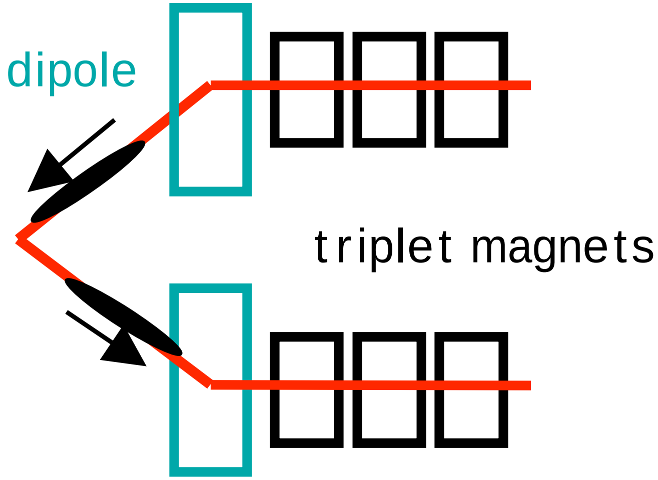
crab cavities &
large crossing angle

Alternative IR schemes



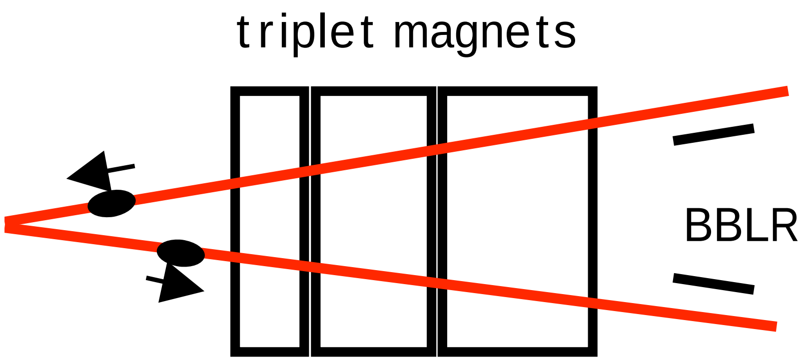
dipole first & small crossing angle

- *reduced # LR collisions*
- *collision debris hit D1*



dipole first & large crossing angle & long bunches or crab cavities

'cheap' IR upgrade in case we need to double LHC luminosity earlier than foreseen



short bunches &
minimum crossing angle & BBLR

- *β^*=0.25 m using conventional NbTi technology*
- *each quadrupole individually optimized (length & aperture)*
- *reduced IP-quad distance from 23 to 22 m*

scenarios for the luminosity upgrade

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Phase 0: steps to reach ultimate performance without hardware changes:

1) collide beams only in IP1 and IP5 with alternating H-V crossing
2) increase N_b up to the beam-beam limit → $L = 2.3 \times 10^{34}$ cm^{-2} s^{-1}
3) increase the dipole field from 8.33 to 9 T → E_{max} = 7.54 TeV

The ultimate dipole field of 9 T corresponds to a beam current limited by cryogenics and/or by beam dump/machine protection considerations.

Phase 1: steps to reach maximum performance with IR and RF changes:

1) modify the insertion quadrupoles and/or layout → β^* = 0.25 m
2) increase crossing angle θ_c by $\sqrt{2}$ → θ_c = 445 μrad
3) increase N_b up to ultimate luminosity → $L = 3.3 \times 10^{34}$ cm^{-2}s^{-1}
4) halve σ_z with high harmonic RF system → $L = 4.6 \times 10^{34}$ cm^{-2}s^{-1}
   - new RF system in LHC providing an accelerating voltage of 43MV at 1.2GHz
   - a power of about 11MW/beam → large estimated cost
   - a longitudinal beam emittance reduced to 1.78 eVs
   - horizontal Intra-Beam Scattering (IBS) growth time will decrease by about $\sqrt{2}$
5) double the no. of bunches n_b (increasing θ_c) → $L = 9.2 \times 10^{34}$ cm^{-2}s^{-1}
   (exceeding ultimate beam intensity →)
   - upgrade LHC cryogenics, collimation and beam dump systems
   - upgrade the electronics of beam position monitors
   - possibly upgrade the SPS RF system and other equipments in the injector chain

Phase 2: steps to reach maximum performance with major hardware changes:

- Injector chain: inject into the LHC at 1 TeV ➔ SPS+ option (2015 ÷ 2017)
  - ➔ beam luminosity should increase
  - ➔ first step in view of an LHC energy upgrade
  - The normalized acceptance doubles in LHC, this should allow doubling the beam intensity by doubling N_b and ε_n (at constant beam-beam parameter $\Delta Q_{bb} \propto N_b/\varepsilon_n$) and the LHC peak luminosity (long range beam-beam compensation schemes mandatory)
  - LHC energy swing is reduced by a factor of 2 ➔ the SC transient phenomena should be smaller and the turnaround time to fill LHC should decrease

  (interesting alternative ➔ compact low-field booster rings in the LHC tunnel)

- LHC ring: install in LHC new dipoles with a operational field of $\geq$ 15÷16 T for the 2020 decade ➔ beam energy around 14 TeV or more
  - ➔ luminosity should increase with beam energy
  - ➔ major upgrade in several LHC hardware components
  - ➔ industrialize low-cost high-field dipoles and quadrupoles

present views on injector upgrade

- Present bottle-neck of the injector complex
  - ➜ The SPS (capture loss, longitudinal stability)
  - ➜ The BPS (space charge)

- Best possible choice for upgrade in energy
  - ➜ The linac (synergy with neutrino-physics needs)
  - ➜ The SPS (synergy with neutrino and flavour physics ? - prerequisite for LHC energy upgrade)

however a PS (at 50 GeV) turns out to be the best choice for CERN especially if the PS magnet consolidation program is not a reliable long term solution

- ➜ the right move towards the (high-priority) LHC performance upgrade
- ➜ an opportunity to develop new fast pulsing SC magnets (for a superconducting PS+ option)

- The 1TeV superconducting SPS should remain the strategic objective
- The real benefit of any proposed upgrade should be fully quantified

Increasing the PS energy will make much easier to operate the SPS

factorization of the luminosity gain

- ♦ factor of 2.3 on L at the ultimate beam intensity (I = 0.58 → 0.86 A)
- ♦ factor of 2 on L from new low-β (β^* = 0.5 → 0.25 m)

  ☹ $T_{turnaround}$ = 10h → $\int Ldt$ = 3 × nominal = 200 fb^{-1} per year

- ♦ factor of 2 on L doubling the number of bunches (may be impossible due to e-cloud) or increasing bunch intensity and bunch length

  ☹ $T_{turnaround}$ = 10h → $\int Ldt$ = 6 × nominal = 400 fb^{-1} per year

{ Consolidation of injectors and completion of LHC
Linac 4 & PS2/PS+
A new SPS & transfer lines injecting in LHC at 1 TeV/c

- ♦ factor of 1.4 in $\int Ldt$ for shorter $T_{turnaround}$ = 5 h
- ♦ factor of 2 on L (2 × bunch intensity, 2 × emittance)

☺ $L = 10^{35}$ $cm^{-2}s^{-1}$ AND $\int Ldt$ = 9 × nominal = 600 fb^{-1} per year

Concluding remarks

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A vigorous R & D programme is required on

- optics, beam control, machine protection, collimation
- high gradient high aperture SC quadrupoles
  - → Nb_3Sn SC wire and cable
  - → radiation-hard design
- RF & crab-cavities
- SC fast ramping magnets
  - → Nb-Ti SC wire and cable
  - → High speed energy removal & radiation-hard design
- for energy upgrade
  - → Nb_3Sn SC wire and cable high field (> 15 T)
  - → Low cost SC & magnets
- detector upgrade should be planned to handle higher L and larger radiation level

Time-scale required 10-12 years➜ START as soon as possible !